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Effects of the 2011 Tohoku Earthquake on VLBI Geodetic Measurements

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Abstract

The VLBI antenna TSUKUB32 at Tsukuba, Japan observes in 24-hour observing sessions once per week with the R1 operational network and on additional days with other networks on a more irregular basis. Further, the antenna is an endpoint of the single-baseline, 1-hr Intensive Int2 sessions observed on the weekends for the determination of UT1. TSUKUB32 returned to normal operational observing one month after the earthquake. The antenna is 160 km west and 240 km south of the epicenter of the Tohoku earthquake. We looked at the transient behavior of the TSUKUB32 position time series following the earthquake and found that significant deformation is continuing. The eastward rate relative to the long-term rate prior to the earthquake was about 20 cm/yr four months after the earthquake and 9 cm/yr after one year. The VLBI series agrees closely with the corresponding JPL (Jet Propulsion Laboratory) GPS series measured by the co-located GPS antenna TSUK. The co-seismic UEN displacement at Tsukuba as determined by VLBI was (-90 mm, 640 mm, 44 mm). We examined the effect of the variation of the TSUKUB32 position on EOP estimates and then used the GPS data to correct its position for the estimation of UT1 in the Tsukuba-Wettzell Int2 Intensive experiments. For this purpose and to provide operational UT1, the IVS scheduled a series of weekend Intensive sessions observing on the Kokee-Wettzell baseline immediately before each of the two Tsukuba-Wettzell Intensive sessions. Comparisons between the UT1 estimates from these weekend sessions and the USNO (United States Naval Observatory) combination series were used to validate the GPS correction to the TSUKUB32 position.

1. Introduction

On March 11, 2011 a magnitude 9.0 earthquake shook the Earth near the northeast coast of Honshu, Japan. The shaking also triggered a major tsunami that hit the coast shortly after the quake. The epicenter of the earthquake was located at a depth of about 29 km at 38.30°N and 142.37°E. This location is about 340 km NNE of the city of Tsukuba, the location of the VLBI telescope TSUKUB32. The co-seismic displacement is primarily in the east-west direction which is consistent with the direction of the Pacific plate velocity at Tsukuba.

The IVS (International VLBI Service for Geodesy and Astrometry) has several network stations in relative proximity to the affected area. Depending on the distance to the epicenter, these stations (e.g., Tsukuba, Kashima, Mizusawa) experienced a co-seismic displacement of several decimeters to meters, and the process of post-seismic relaxation is still ongoing. While these stations dropped out of the IVS observing plan immediately following the quake, every effort was undertaken to reestablish observing as soon as possible. This is particularly important in order to precisely determine the new position and velocity. Tsukuba commenced observing in 24-hour sessions about one month after the event.

Tsukuba plays a special role in the IVS observing plan, as it constitutes a non-redundant endpoint of the baselines of the weekend Intensives (Int2 and Int3). Given the displacement and the continuing relaxation caused by the earthquake, it is no longer valid to determine the a priori position of Tsukuba from its pre-earthquake position and velocity. As the position is held fixed in the dUT1 determination, any error in the position at the epoch of the session will propagate directly into the dUT1 estimate.

2. Post-earthquake Motion

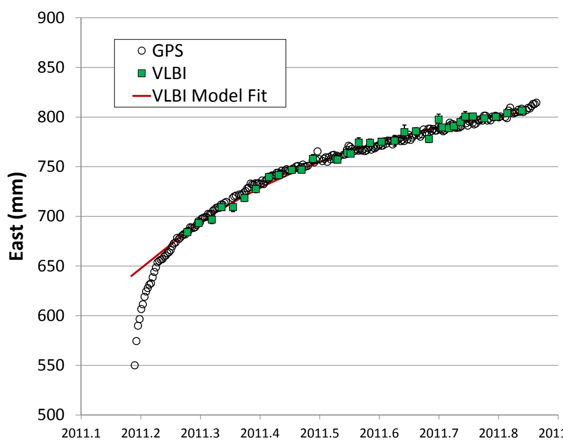

Figure 1. East VLBI and GPS displacements.

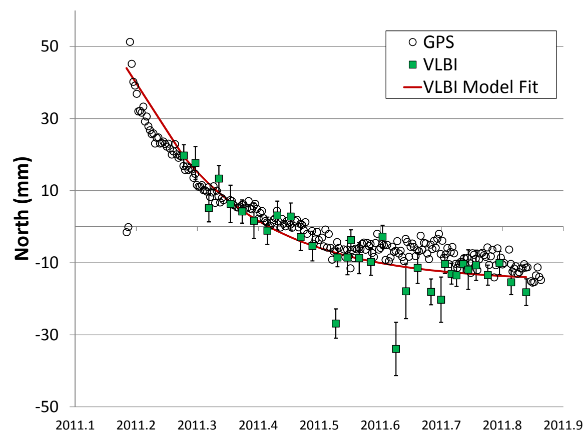

Figure 2. North VLBI and GPS displacements.

In our standard terrestrial reference frame CALC/SOLVE solutions, we estimate site positions and velocities as global parameters. To investigate the behavior of the position of TSUKUB32, we modified the solution to estimate the mean TSUKUB32 position for each VLBI 24-hour experiment. Figures 1, 2, and 3 show our solution for the local site coordinate variation for TSUKUB32 due to the earthquake. Offsets, rates, and annual and semi-annual terms were estimated from VLBI or GPS series before the earthquake and removed from each series to generate the plotted series. We have compared the post-seismic trends from VLBI and GPS measurements. In these figures, we also show the trend derived from daily GPS position series from JPL (courtesy of Mike Heflin).

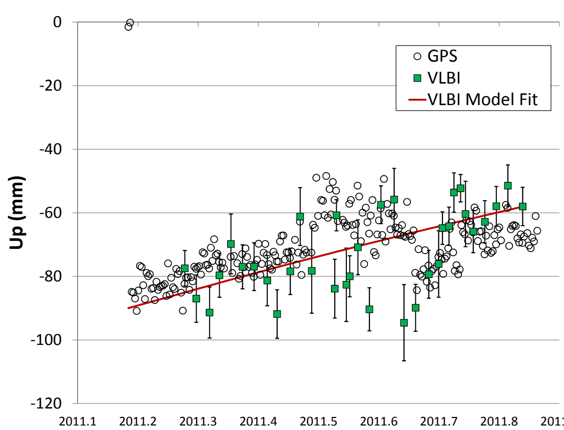

Figure 3. Vertical VLBI and GPS displacements.

There is clear nonlinear variation after the earthquake in all components. The East and North components show clear transient behavior. In the vertical, there is some apparently systematic variation seen in the GPS estimates from 2011.5–2011.8 that is not seen in the VLBI estimates (although they are very noisy). We fit the post-seismic VLBI data using a transient decay model, where t_0 is the epoch of the earthquake:

$$X(t) = X_0 + X_1[1 - exp(-(t - t_0)/\tau_c)].$$

The fits gave characteristic decay times, τ_c, of 131 days and 62 days for the East and North components, respectively. The corresponding co-seismic amplitudes, X_0, were 640 mm and 44 mm. The models fit the VLBI data fairly well for times greater than about one month after the earthquake. In general there is good agreement between the horizontal trends of the VLBI and GPS series. The first post-earthquake GPS point is from March 12, one day after the earthquake. The post-earthquake GPS East and North displacements for this measurement were 550 mm and 52 mm. The first month of GPS values indicate that the East and North positions decreased much more sharply than the above transient model derived from the VLBI data. A simple transient model is not sufficient to model the observed GPS variation over the whole range of GPS values. The estimates of the co-seismic offsets from VLBI data are clearly inaccurate because of the lack of VLBI data directly after the earthquake.

3. Intensive Sessions

3.1. Operational Correction

The IVS carries out operational one-hour Intensive sessions every day of the week to determine rapid UT1–UTC. The Kokee–Wettzell baseline is observed from Monday through Friday in Int1 sessions. On the weekend, the Int2 Intensives observe on the Tsukuba–Wettzell baseline. After the earthquake, the IVS set up a special set of sessions to observe on the Kokee–Wettzell baseline immediately before the regular Int2 sessions. These sessions provided UT1 weekend operational measurements until a correction for the Tsukuba position variation was determined. During the period after the earthquake, USNO included the special weekend Kokee–Wettzell UT1 data in the usno_finals.daily combination, but not the Tsukubu–Wettzell UT1 data.

Analysis of the Intensive experiments requires that the positions of the two stations of single baseline networks be well known so that their positions can be fixed. Any error in the a priori positions will propagate to UT1 error. For the Tsukuba-Wettzell baseline, the sensitivities of UT1 to errors in UEN at Tsukuba are ΔUT1/ΔU = +0.25 μsec/mm, ΔUT1/ΔE = -1.50 μsec/mm, and ΔUT1/ΔN = -0.85 μsec/mm. Since the Tohoku earthquake, the position of TSUKUB32 has continued to change non-linearly (after the initial co-seismic jump) relative to the long-term trend of TSUKUB32 prior to the earthquake. We have investigated procedures for determining a good a priori position for TSUKUB32 suitable for Intensive analysis.

We have used the change in GPS position since the earthquake (shown in Figures 1–3) to correct the VLBI position. The Tsukuba Int2 sessions have been analyzed with this correction to determine UT1. USNO routinely generates a geodetic technique combination EOP (Earth orientation parameter) solution, usno_finals.daily, for the International Earth Rotation and Reference Systems Service (IERS). To determine how well we have made the correction, Nick Stamatakos (USNO) has performed test combination solutions that incorporate our corrected Tsukuba–Wettzell UT1 series. Figure 4 shows the Tsukuba–Wettzell UT1 residuals relative to the test version of usno_finals.daily without any correction for the earthquake. Figure 5 compares the residuals of the corrected Int2 series with the residuals of the special weekend Intensives on the Kokee–Wettzell baseline. Table 1 compares the residual differences (bias and wrms) between the Kokee–Wettzell and the Tsukuba–Wettzell Intensive series and the usno_finals.daily series. The corrected UT1 Tsukuba–Wettzell Int2 series agrees with the combination series at the same level as the Int1 and pre-earthquake Int2 UT1 series.

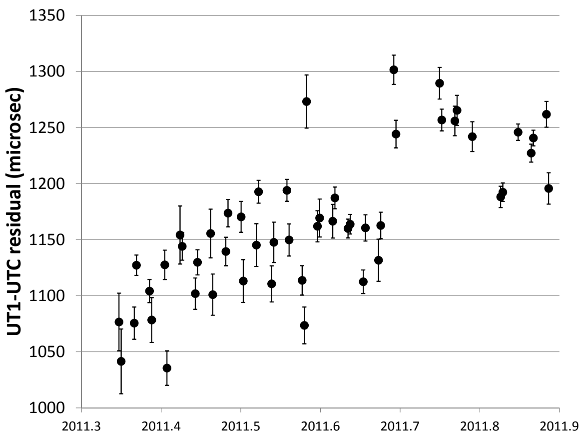

Figure 4. UT1 differences with respect to the test version of usno_finals.daily without Tsukuba position correction.

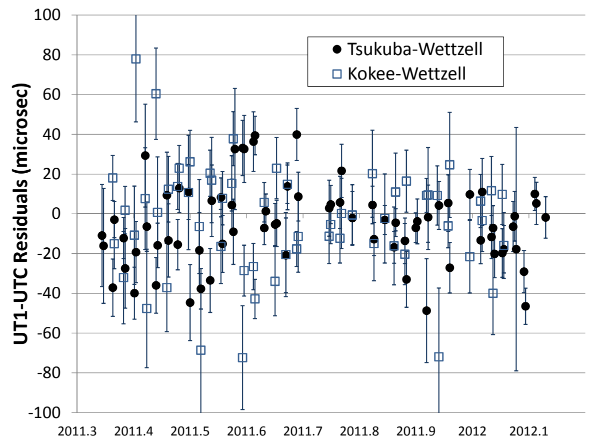

Figure 5. UT1 differences with respect to the test version of usno_finals.daily with the Tsukuba position correction.

Table 1. Differences between Intensive series and the USNO combination.

Baseline	Period	Bias	WRMS
		[μsec]	[μsec]
Kokee–Wettzell	Special weekend since earthquake	−2.8	14.4
Tsukuba–Wettzell	Int2 since earthquake	−5.9	15.4
Kokee–Wettzell	Int1 2009–2011	−3.7	15.1
Tsukuba–Wettzell	Int2 2010	−10.1	15.7

3.2. Tsukuba Position Service

We are currently providing a post-seismic correction for the position of TSUKUB32. It is based on the GPS series generated by JPL (Mike Heflin). For each point in the post-earthquake non-linear series, we make a linear fit over the last 30 days to smooth the series and provide a prediction forward (for operational use). Files are updated every day with the latest GPS data. The JPL time series are updated using final orbits computed from the previous week of observations. Depending on the day of the week that a position is desired, the latency of the correction can be 8–14 days. Files are provided at `ftp://gemini.gsfc.nasa.gov/pub/misc/dsm/tsukuba`.

4. R1 Sessions

The IVS observes 24-hour sessions on a regular basis typically using a network of 7–10 stations. TSUKUB32 is a core station in the operational weekly R1 network. It observed until 7 March 2011 (four days before the earthquake) and resumed observing on 11 April 2011. We considered three possible options for handling TSUKUB32 in analysis: 1) delete the TSUKUB32 data entirely, 2) estimate the TSUKUB32 position for each 24-hour session (current GSFC procedure), and 3) apply the post-earthquake GPS correction to the a priori Tsukuba position without estimation of its position for each session.

TSUKUB32 is very important for the network geometry. Estimating the TSUKUB32 position for each session weakens the data from TSUKUB32. Applying the GPS correction for post-earthquake change strengthens the contribution from the TSUKUB32 data and reduces the corresponding EOP uncertainties. The results in Table 2 show that correcting the position of Tsukuba yields the best formal EOP uncertainties and clearly improves the wrms agreement of polar motion estimates with GPS.

Table 2. EOP uncertainties and IGS differences.

	Uncertainties					IGS WRMS Differences		
	x_p	y_p	UT1–UTC	$d\psi \sin \varepsilon_0$	$d\varepsilon$	x_p	y_p	LOD
	$[\mu as]$	$[\mu as]$	$[\mu s]$	$[\mu as]$	$[\mu as]$	$[\mu as]$	$[\mu as]$	$[\mu s/d]$
No Tsukuba	91	82	4.1	65	69	111	120	19.5
Estimate Tsukuba	68	67	3.2	44	45	112	112	16.0
Correct Tsukuba	54	60	2.5	44	45	90	90	16.3

5. Conclusion

Post-seismic relaxation is ongoing, and the position of Tsukuba is continuing to change non-linearly relative to the pre-earthquake long-term rate. The post-earthquake variations estimated from VLBI and GPS measurements are in good agreement, which allows us to use the more frequent GPS measurements to determine a correction for the VLBI post-earthquake position. The VLBI Int2 UT1–UTC estimates from the Tsukuba–Wettzell baseline Intensives are clearly better after correcting the VLBI a priori position of Tsukuba using GPS data. Agreement of the corrected Int2 UT1–UTC estimates with the USNO combination series, usno_finals.daily, is at the level of agreement of the Int1 and pre-earthquake Int2 series. We have developed a procedure to compute the latest post-earthquake GPS correction operationally for use in rapid service analysis of Intensive sessions involving TSUKUB32. We have found that VLBI polar motion agrees better with IGS EOP when the post-earthquake GPS correction is applied in 24-hour R1 session analysis.

Acknowledgements

We thank Mike Heflin for bringing the latest JPL site position solution online earlier than originally planned and Nick Stamatakos for testing our solutions in test USNO combinations.